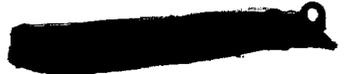


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A STUDY OF HYPERSONIC AIRCRAFT

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A STUDY OF HYPERSONIC AIRCRAFT

By Douglas E. Wall*
NASA Flight Research Center

INTRODUCTION

A study is being made at the NASA Flight Research Center to determine the gross characteristics of future hypersonic aircraft, without the refinement of configuration optimization. The characteristics defined by this study are to be used as a guide in assessing the need for future hypersonic flight research.

Some of the possibilities and characteristics of future hypersonic aircraft as envisioned by Flight Research Center engineers are discussed in this paper. In this space age one might logically ask why we are still concerned with airplanes. The answer is that the aerodynamic lift and air-breathing propulsion available from the atmosphere continue to appear attractive in future applications. This is clearly evident for systems requiring sustained cruise operation.

Figure 1 shows, graphically, the development of aircraft speeds. The shaded areas indicate probable future extensions. The steep slope of the rocket-powered research airplanes indicates the rapid technological advancements that have been made. This trend could possibly be reflected in future military aircraft, resulting in flight at hypersonic speeds. If this occurs, it may provide the developed engines and service experience necessary for development of commercial cruise aircraft operating at hypersonic speeds.

Since hypersonic aircraft are so dependent on the mode of propulsion, some of the proposed fuels and some candidate propulsion systems and their flight regions of operation are reviewed in the following sections. In the subsequent discussion, an assessment is made of each class of hypersonic aircraft.

HYPERSONIC PROPULSION

Flight in the sensible atmosphere at hypersonic speeds will require at least two, and possibly three or four, modes of propulsion for some of the vehicle systems. Various tradeoffs will be possible, based on the selection of fuels and the flight region of operation. The performance of the liquid-hydrogen air-breathing engines and the liquid-hydrogen liquid-oxygen ($\text{LO}_2\text{-LH}_2$) rocket motor is compared in figure 2. The ability of the air-breathing engines to produce significantly more thrust per pound of carried propellant than the rockets shows their suitability for cruise applications.

*Airborne Hypersonic Research Project Manager



Candidate Fuels for Hypersonic Cruise

The following table presents various characteristics of three fuels:

| Fuel | Lower heating value, Btu/lb (fuel) | Apparent heat sink, Btu/lb fuel | Density, lb/cu ft | Actual heat release, *Btu/cu ft (air) | Available heat sink, *Btu/cu ft (air) | Volumetric fuel requirements, *cu ft fuel/cu ft air |
|-----------------|------------------------------------|---------------------------------|-------------------|---------------------------------------|---------------------------------------|---|
| Liquid hydrogen | 52,000 | 5,800 | 4.42 | 115 | 12.95 | 0.09 |
| Liquid methane | 20,000 | 1,100 | 26.5 | 88.6 | 4.88 | 0.03 |
| Hydrocarbon | 18,700 | 800 | 49.9 | 99.8 | 4.26 | 0.02 |

*Per cubic foot of inlet air for stoichiometric combustion.

The first three columns show the familiar values associated with fuels; the last three assess the fuels on the basis of each cubic foot of air entering the inlet for complete combustion. The last column shows the liquid tank volume required for each cubic foot of inlet air. As indicated, liquid-hydrogen fuel gives the highest heat release for producing thrust. It is also clearly superior as a heat sink for operation at the higher flight speeds. Its chief disadvantage is the large volume requirement for fuel storage; in the smaller aircraft this results in high drag which offsets the increased heat release. At first glance, liquid methane appears to be attractive. However, the last three columns indicate that the small increase in available heat sink over the hydrocarbons would not warrant the loss in performance or the increase in tank volume.

Modes of Propulsion

Both turbojet engines and rocket motors were used extensively in the Flight Research Center study. Since both are familiar propulsion systems, no further discussion is believed to be necessary. In contrast, ramjets are not as familiar and, thus, warrant some discussion.

Subsonic combustion ramjet.- At the higher supersonic flight speeds, the subsonic combustion ramjet engine is clearly superior to the turbojet, but flight speeds greater than Mach 1 are usually required for ramjet acceleration of large vehicles. Thus, the aircraft must be accelerated to the ramjet take-over speed with rocket or turbojet power. The inlet air in a subsonic combustion ramjet is compressed and slowed down, which results in a terminal shock. The flow behind the terminal shock where combustion is taking place is subsonic. At the higher hypersonic speeds, the internal static pressure and temperature become extremely high. With present state-of-the-art materials, this engine and portions of the inlet must be regeneratively cooled by the fuel. At extremely high speeds, the fuel required to cool the engine and inlet exceeds the fuel flow required to cruise the aircraft. At higher speeds, cruise efficiency drops rapidly.

Supersonic combustion ramjet.- At the high hypersonic flight speeds, the supersonic combustion ramjet may be superior to the subsonic combustion ramjet. The inlet air of the supersonic combustion ramjet is not compressed nor slowed down as much as the air in the subsonic combustion engine; consequently, the flow remains supersonic throughout the combustion and expansion processes. As a result, the internal static pressures and temperatures are less than those in the subsonic engine.

Region of Operation

The probable region of operation for the air-breathing engines is shown in figure 3. Although there is considerable overlap for each of the propulsion systems, the plot shows the relative order of each. It is noted that flight at the higher speeds would require operation at very high external aircraft-skin temperatures. It is doubtful that aircraft would cruise at speeds high enough to require active cooling of major portions of the aircraft. The choice of the mode of propulsion will depend not only on relative performance of the ramjet engines but also on maximum cruise range and minimum block time when coupled to an optimum aerodynamic configuration.

HYPERSONIC AIRCRAFT

Long-Range Cruise Aircraft

Long-range hypersonic-cruise aircraft are in an early stage of study. The probable ranges and cruise speeds for commercial aircraft, looking 10 to 20 years into the future, with ranges greater than 4,000 nautical miles are shown in figure 4. Since the large aircraft must necessarily accelerate and decelerate at low rates, it is interesting to note that the ratio of cruise range to ascent plus descent range, k , decreases from 5.0 for a supersonic transport to 2.6 for a Mach 8 hypersonic cruise aircraft. To achieve flight speeds significantly above Mach 8 for the same range, the vehicle would probably be classed as an acceleration-boost-glide aircraft rather than a cruise aircraft because of the low k value. In addition, Mach 8 to 10 cruise speeds could result in commercial aircraft ranges reaching half way around the world. Therefore, higher Mach number cruise may not be necessary. Cruise above a Mach number of 3 will require extensive analyses of configuration tradeoffs, inlet-engine matching, and cooling requirements. The study has not progressed far enough to determine whether these ranges could be met with practical airplanes; therefore, they should be viewed only as probable goals. A configuration for a Mach 6 to 8 cruise aircraft (fig. 5) is being studied. The vehicle uses liquid-hydrogen fuel and is a blended-body delta-wing configuration. With estimated takeoff gross weights between 500,000 and 700,000 pounds, the aircraft could carry from 200 to 400 passengers.

Medium-Range Cruise Aircraft

Medium-range cruise aircraft include vehicles with military applications that would cruise at hypersonic speeds, with total ranges of approximately 3,000 nautical miles.

Figure 6 shows a possible configuration of a liquid-hydrogen fueled hypersonic-cruise aircraft with turboramjet engines. The vehicle would cruise at a Mach number of 5 to 6. Figure 7 illustrates a comparable hydrocarbon-fueled hypersonic-cruise aircraft with turboramjet engines. This vehicle would also cruise at a Mach number of 5 to 6. For Mach 6 cruise, both airplanes had comparable ranges, on the order of 3,000 nautical miles. The take-off gross weight of both aircraft was approximately the same; however, the hydrocarbon-fueled aircraft was considerably smaller. This size difference indicates that the increased performance with the hydrogen fuel was offset by the high drag that resulted from the large fuel-tank volume.

Several technology advancements are required to develop future hydrogen-fueled hypersonic aircraft utilizing air-breathing propulsion. A hypersonic research aircraft was studied at the Flight Research Center as a means of providing these advancements (fig. 8). The airplane weighed 80,000 pounds and was capable of periods of extended cruise above a Mach number of 6.

Acceleration-Boost Aircraft

In recent years many studies have been made of earth-to-orbit transportation systems. Similar studies have been performed at the Flight Research Center for a two-stage-to-orbit system to supply a hypothetical space station. These studies show that the first-stage aircraft could be powered either by rockets or by air-breathing engines. The air-breather, with its ability to cruise, could provide increased offset orbital capability, thereby providing several opportunities for insertion each day. This capability would be an advantage for emergency orbital supply. If increased offset orbital capability is not required, the type of propulsion system that should be used in the first stage is not readily apparent. However, if rocket propulsion is assumed for the second-stage vehicle, certain gross characteristics may be determined from a parametric study. Figure 9 shows the effect on the second-stage launch weight of varying the rocket specific impulse to place a 20,000-pound payload into orbit. This figure shows that high staging velocities must be realized with present state-of-the-art rockets to produce reasonable second-stage launch weights. It also shows that advances in rocket performance could either reduce the staging Mach number or the launch weight. Improvements in inert weight fraction have a similar effect.

Figure 10 shows the combined effect of rocket specific impulse and inert weight fraction on the second-stage launch weight. System weights may be roughly estimated by assuming that the weight of the second-stage is 40 percent of the takeoff total vehicle system weight. Thus, a 400,000-pound second-stage launch weight would require a vehicle system total takeoff gross weight of 1,000,000 pounds. The higher staging velocities, improved rocket specific impulse, and improved inert mass fractions would significantly reduce the total weight of the system, thereby allowing a lighter vehicle system. Therefore, advancements in the state of the art would provide a reasonable system that could be operated from existing runways, and would insert a larger payload fraction into orbit.

Sonic-Boom Overpressures

Limited experimental flight data have been accumulated on sonic-boom overpressures in relation to such factors as community tolerance, structural damage, and atmospheric effects. Data from small- and medium-sized aircraft such as supersonic interceptors and B-58 bombers showed effects which could not be predicted by using only form factor. Latest theory indicates that there is a contribution due to form factor and another contribution due to lift. Since the B-58 is not a large supersonic aircraft, the exact lift effects of a large supersonic transport or hypersonic-cruise aircraft have not been verified. Because of this lack of experimental flight verification, it was considered premature to predict sonic-boom overpressures for the hypersonic configurations studied. A Flight Research Center flight test program is planned with a B-70, which has the capability of a large form factor and a significant lift, to experimentally determine the sonic-boom overpressures over a range of flight conditions.

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CONCLUDING REMARKS

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Results obtained thus far in the Flight Research Center hypersonic-aircraft study indicate that:

The long-range hypersonic-cruise aircraft offers sufficient potential to warrant serious consideration for future missions.

Mach number 5 to 6 cruise aircraft designed for hydrocarbon fuel may be competitive with those designed for hydrogen fuel for ranges of approximately 3,000 nautical miles.

First-stage recoverable boosters must stage at reasonably high velocities to reduce the takeoff gross weight. Advancements in the state of the art would provide a booster small enough for takeoff from conventional runways.

Hypersonic aircraft of the type studied will require takeoff velocities of 175 knots to 200 knots. Landing and approach speeds may be comparable to current jet aircraft.

Future aircraft must be designed to conform to acceptable sound levels and sonic-boom overpressures. They also should be designed to allow takeoff from existing runways.

Airports of the future may require storage of liquid-hydrogen fuel and hydrocarbon fuel. In addition, it may be practical to install liquid-hydrogen-producing plants at the major airport terminals.

AUTHOR

SYMBOLS

I_{SP} specific impulse, $\frac{\text{thrust (rocket)}}{\text{propellant flow rate}} = \frac{\text{thrust (air-breather)}}{\text{fuel flow rate}}$

$$k = \frac{R_{\text{cruise}}}{R_{\text{ascent}} + R_{\text{descent}}}$$

R_{cruise} range for cruise portion of flight, nautical miles

$R_{\text{ascent}},$
 R_{descent} range for ascent and descent portions of mission, respectively,
nautical miles

W_i inert weight ($W_0 - W_p - W_{PL}$), lb

W_0 weight of second stage at time of launch, lb

W_{PL} weight of payload in second stage, lb

$\left(\frac{W_i}{W_0}\right)_{II}$ inert weight fraction of second stage

$\left(\frac{W_{PL}}{W_0}\right)_{II}$ payload in percent of second-stage launch weight

HISTORY OF AIRCRAFT SPEEDS

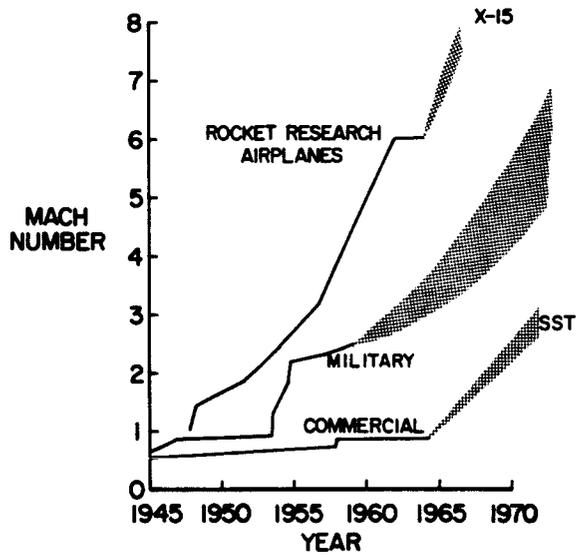


Figure 1

ENGINE-PERFORMANCE COMPARISON LIQUID-HYDROGEN FUEL

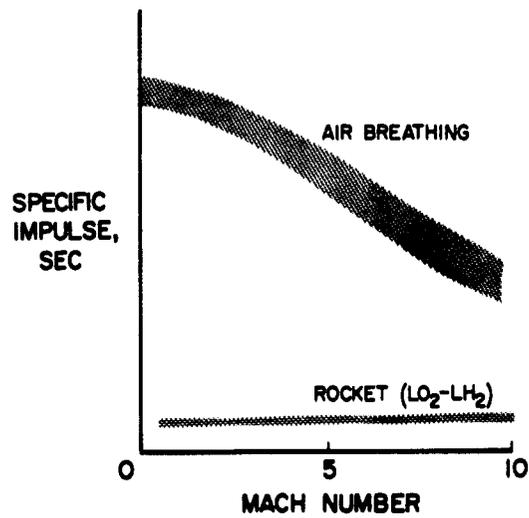


Figure 2

PROBABLE OPERATIONAL ENVELOPE
FOR AIR-BREATHING ENGINES

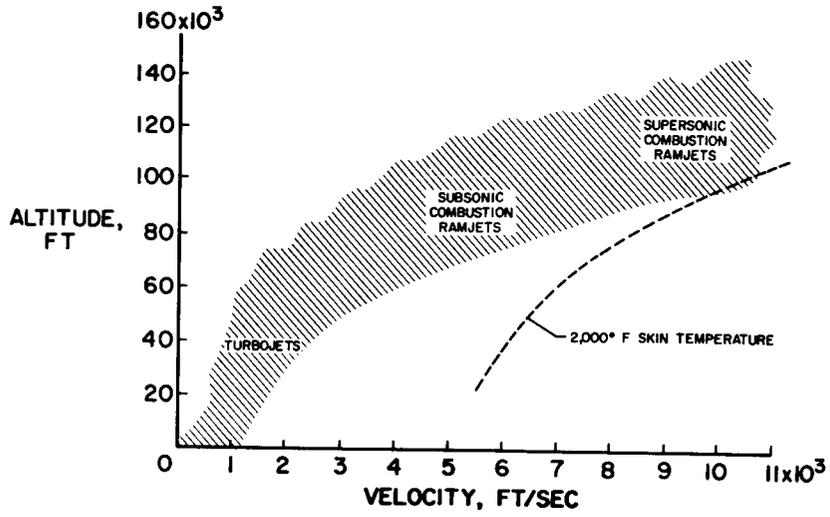


Figure 3

PROBABLE RANGES
FOR FUTURE CRUISE AIRCRAFT

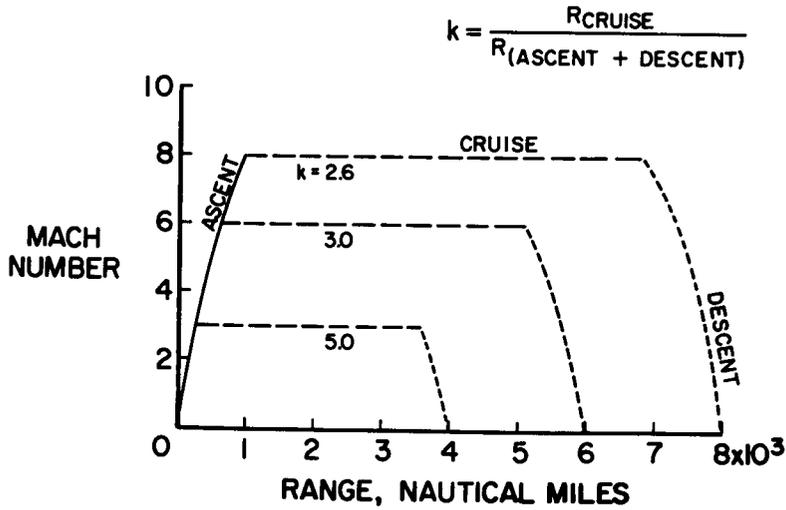
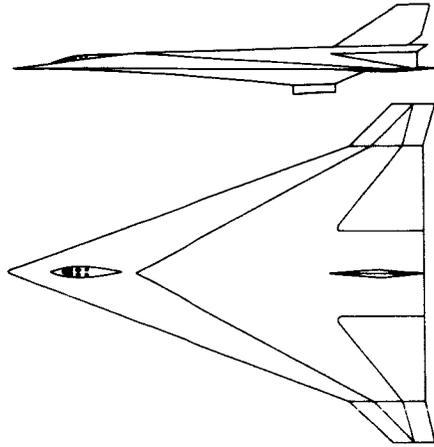


Figure 4

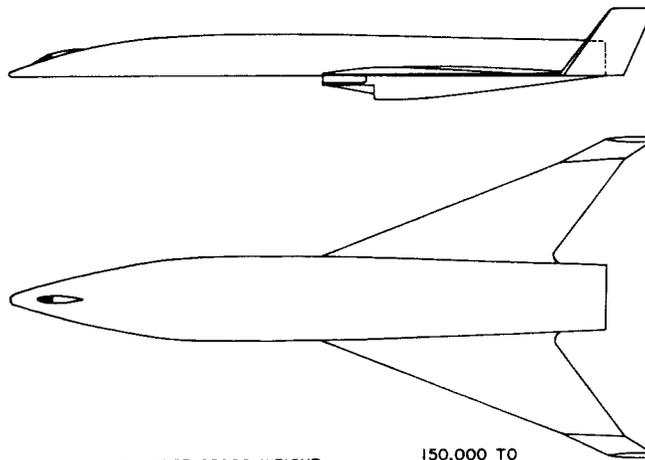
HYPERSONIC LONG-RANGE CRUISE AIRCRAFT
LIQUID-HYDROGEN FUEL



TAKEOFF GROSS WEIGHT 500,000 TO 700,000 LB
CRUISE SPEED MACH 6 TO 8

Figure 5

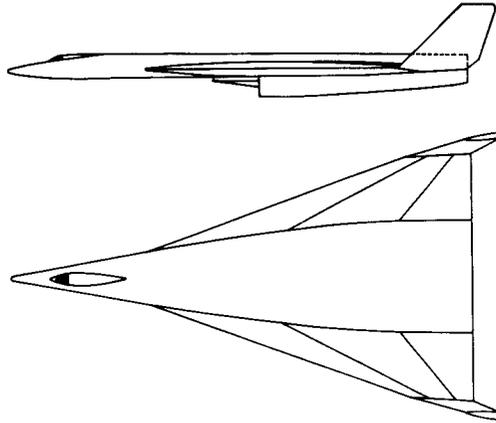
HYPERSONIC MEDIUM-RANGE CRUISE AIRCRAFT
LIQUID-HYDROGEN FUEL



TAKEOFF GROSS WEIGHT 150,000 TO 200,000 LB
ENGINES TURBORAMJETS
TOTAL RANGE (NO RESERVES) ≈ 3,000 NAUTICAL MILES
CRUISE SPEED 5 TO 6

Figure 6

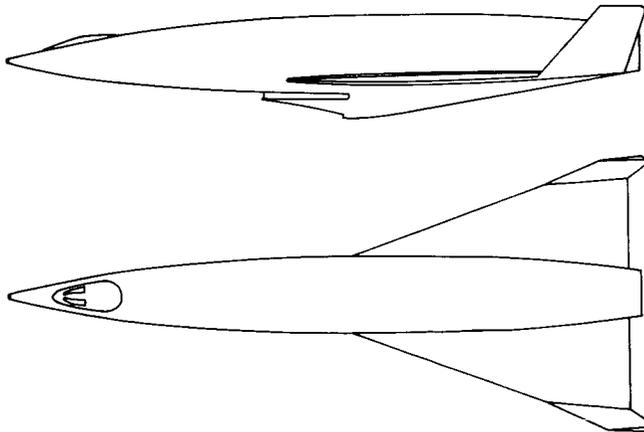
**HYPERSONIC MEDIUM-RANGE CRUISE AIRCRAFT
HYDROCARBON FUEL**



TAKEOFF GROSS WEIGHT 150,000 TO 200,000 LB
ENGINES TURBORAMJETS
TOTAL RANGE
(NO RESERVES) ≈3,000 NAUTICAL MILES
CRUISE SPEED 5 TO 6

Figure 7

**HYPERSONIC RESEARCH AIRCRAFT
LIQUID-HYDROGEN FUEL**



TAKEOFF GROSS WEIGHT 80,000 LB
ENGINES TURBORAMJETS
CRUISE SPEED > MACH 6

Figure 8

SPECIFIC-IMPULSE EFFECT

$$\left(\frac{W_i}{W_0}\right)_{II} = 20 \text{ PERCENT}$$

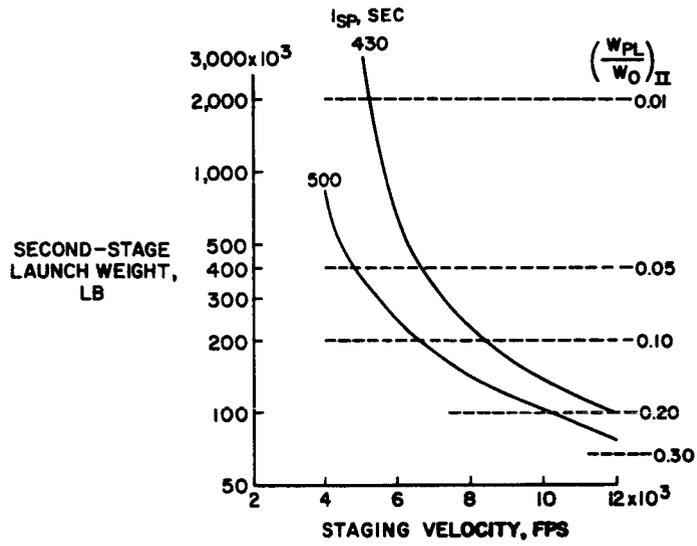


Figure 9

SPECIFIC-IMPULSE AND INERT-WEIGHT-FRACTION EFFECT

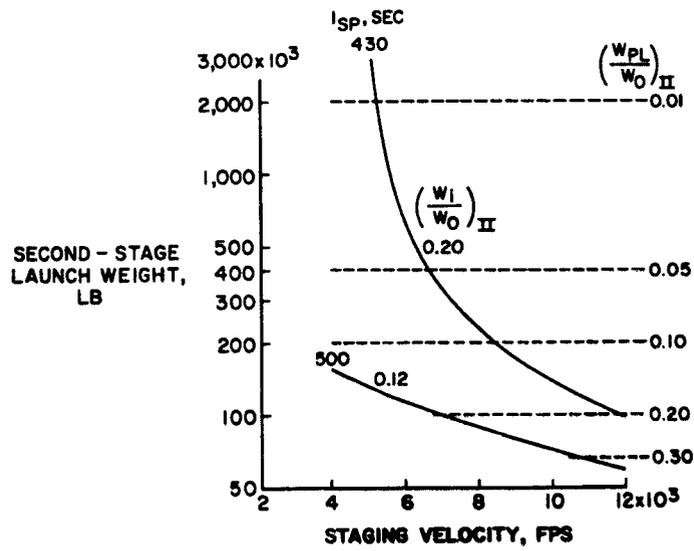


Figure 10